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A GIS-based approach for evaluating the potential of biogas production from livestock manure and crops at a regional scale: A case study for the Kujawsko-Pomorskie Voivodeship

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A B S T R A C T

In Poland, the promotion of the development of biogas plants was intensified under legal regulations. The potential expansion prompts the need for the assessment of a variety of environmental and geographical constraints as well as technical and economic factors, which ensure socio-economically and ecologically sound biogas development. In this paper, both spatial and non-spatial data were integrated to the GIS model to help determine the optimal sites for installing anaerobic digesters (AD). The focus was placed on animal manure (from cattle and pig populations), and co-substrates such as crop silage. Furthermore, the paper provides insight into the structure of cost and benefits in order to examine what incentive measures suffice to force biogas development and how much biogas feedstock could cost to make investments viable. The techno-economic assessment was carried out for combined heat and power generation and bio-methane injection into the gas grid. The methodology was applied to Kujawsko-Pomorskie Voivodeship.

Contents

1. Introduction

In Poland, agricultural biogas generation is still in an early phase of development. Thus, to strengthen its promotion, the Council of Ministers adopted on 13th July 2010 the document entitled “Development of agricultural biogas plants in Poland in 2010–2020”, which aims for a very ambitious goal of increasing the biogas power

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capacity to 3000 MW from the current installed 77 MW (including the capacity of 7.5 MW generated by 7 agricultural biogas power plants) [1]. According to this document biogas generated from the agriculture and the food processing industry would supply approx. 1.7 billion m^3 of bio-methane per year to meet 10% of the demand for natural gas and provide in addition, 125 GWh of electricity and 200 GWh of thermal energy [2].

Among many biogas feedstock sources, animal manure and energy dedicated crops are widely promoted by the legal document [2] in order to drive rural development. The objective of this study was to assess the prospects for biogas development by identifying the deployment of basic biogas feedstock such as animal manure and energy crops. Addressing concerns over conflicts between land use for energy rather than food and fodder production, the study dealt with the potential of the farmland and energy crops.

As spatial factors play a key role in the process of site selection, the methodology was developed using the Geographical Information System (GIS) enabling to integrate a variety of environmental aspects (i.a. maintenance of nature conservation, water protection), technical criteria (i.a. proximity to a power network or to a gas grid) and economic criteria (transportation costs of biogas feedstock, proximity to the power network and the natural gas grid, cost and benefits of the biogas production). Many studies carried out within the GIS environment were devoted to the evaluation of optimal locations for various power plans [3,4], to the distribution of biomass potential [5–7], and to the assessment of technical and economic potential [7–10]. The method proposed aggregates georeferenced and statistical data set as well as information coming from different studies regarding technical and economic evaluations. Moreover, the non-spatial data was geocoded to produce spatially related data.

Biogas has so far been predominantly utilised in the combined heat and power (CHP) plants to generate electricity and heat. In order to increase the overall efficiency of biogas use throughout the whole year, due to a common problem of seasonal fluctuation in heat demand, the upgraded bio-methane to natural gas quality can be injected into the natural gas grid. Therefore, the paper addressed both technical alternatives of biogas utilisation under current legal framework and economic conditions. It must be noted that the exemplary findings presented here depend on unpredictable fluctuating variables set out as constant to enable the assessment. However, the methodology allows one to adjust different variables to incorporate different assumptions.

The model was applied to the Kujawsko-Pomorskie Voivodeship as a case study for the demonstration, since no such study is available for the region. So far, in this region 7 biogas power plants have been operating at dump and sewage treatment plants and one in Liszkowo (2.1 MWe) utilising residues from the food industry [1].

2. Scope of the study and methodology

The method developed using the ARCGIS 9.3 software allows one to evaluate the potential and geographical distribution of biogas feedstock (animal manure and selected crops) at a regional scale and determine the preliminary sites for biogas development by including ecological, technical and economic criteria. In addition, the mathematical functions developed based on collected dataset from the literatures allow for the techno-economic evaluation of biogas projects under constant set variables.

The workflow diagram describing the stepwise methodology is illustrated in Fig. 1. The following actions were performed: first, the zones suitable for biogas development were pre-selected with respects to the exclusive and selective criteria. In a second step, the data on the animal farms was gecoded and the spatial density of the animal manure was computed to identify optimal sites within those pre-selected zones. Next, the arable land was mapped within certain distances from biogas plant sites to assess the share of required land for biogas dedicated crop planting in the total arable land. Similar spatial analyses were carried out for selected crops. The assessment of technical and economic potential was carried out for energy production with combined heat and power technologies as well as the bio-methane feeding into the natural gas grid.

2.1. Biogas feedstock

A variety of organic feedstocks can be used for biogas production as long as they contain carbohydrates, proteins, fats and hemicelluloses as their main components [11]. Due to a high hectare yield (30–50 t/ha) under moderate agro-climate conditions, maize is widely used as co-substrate in many anaerobic digesters [12–14]. Sugar beets (up to 35 t/ha) or potatoes (up to 50) can also achieve a high yield but due to operational problems these crops are very seldom used [12]. Apart from maize silage the most frequent co-substrates for the fermentation are grass silage and cereals [12,15,16]. Exemplary biogas yield with respect to dry matter content and volatile solids of different biogas feedstocks are outlined in Table 1.

The optimal mix of biogas feedstock depends on the choice of fermentation systems with respect to economic criteria and the availability of biogas feedstock. Nonetheless, wet fermentation systems dominate with total dry matter (DM) of up to 15%, which based mostly on animal slurry with addition of co-substrates to increase the content of organic material for achieving a higher gas yield [11,17,19,20]. In Poland, the basic biogas feedstock fed into agricultural biogas plants is animal manure, whose mass percentage varies from 60% to 100%. The main co-substrate is maize silage with a mass share between 16% and 28% and the rest is organic waste. In a situation like this, the focus was placed on assessing the potential of farm manure under the assumption of wet fermentation with 15% DM of the total feedstock mix. The required amount of co-substrates was estimated based on the identified quantity of animal by-products according to the formula:

$$\sum S_{cs} = \frac{0.15 \times S_m - DM_m \times S_m}{\sum DM_{cs} - 0.15} \quad [\text{t/y}] \tag{1}$$

where S_{cs} is the amount of co-substrates (maize silage and cereals silage) [t/y], S_m is the annual quantity of animal feedstock, DM_m is dry matter of animal manure and slurry, DM_{cs} is the dray matter of co-substrates (Table 1).

2.2. Pre-selection procedure for biogas development zones

The pre-selection of sites for biogas development must fulfil certain conditions, since the aim is to enhance the environmental and economic benefits of biogas use and to mitigate conflicts related to the biogas production process and its facilities. Consequently, the several selective and exclusive criteria were defined, as outlined in Table 2, to facilitate the siting process in the GIS environment. With respect to the potential impact associated with noise, fumes, visual intrusion and increase in local traffic, ADs are located within a certain distance of residential areas and visually sensitive landscapes. Furthermore, in accordance with the Nature Protection Act, biogas plant construction is prevented in nature reserves and other protected areas [21]. Within landscape areas and the Natura 2000 network, biogas plant projects may not be strictly excluded. However, such exceptions are only permitted if the environmental impact assessment demonstrates that an impact would be tolerable. However, on a regional scale, according to the precautionary principle, the entire area under protection as well as forests, roads and wetlands are excluded from the biogas development sites and buffer zones were defined to establish the minimum distance as

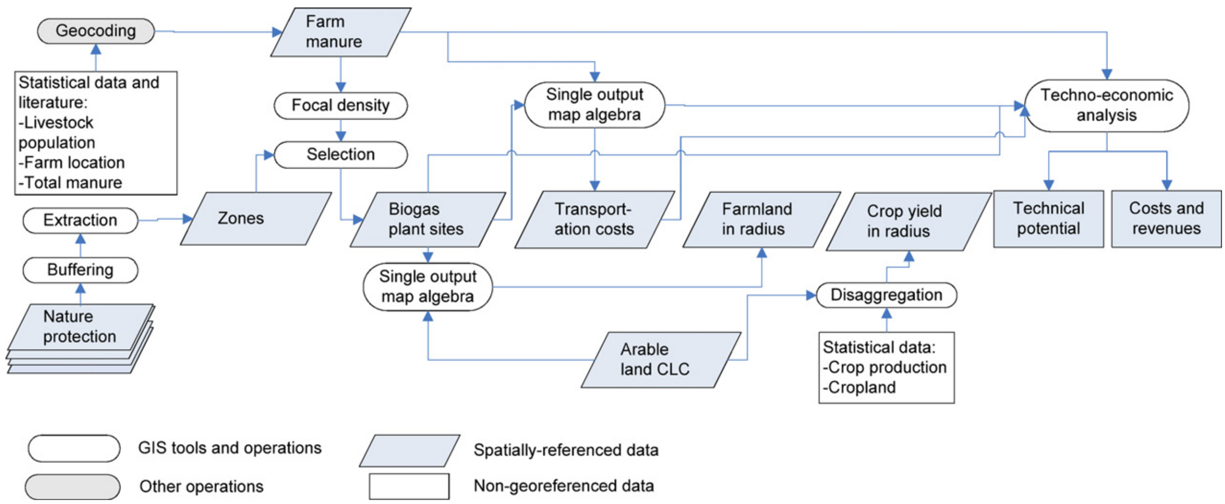

Fig. 1. Flow diagram describing operation steps of the method.

Table 1
Exemplary biogas yield, dry matter and volatile solids of different crops and animal manure.

Substrate	Dry matter, % DM	Volatile solids, %VS	Biogas, m^3/Mg VS	Methane content, %
Maize silage	31	94	577	56
GPS rye silage	30	92	580	56
GPS wheat silage	32	92	580	56
Wheat grain	86	98	680	51
Rye grain	86	98	690	52
Grass silage	30	80	550	54
Sugar beets	23	90	800	53
Cattle manure and slurry	11	80	320	58
Pig slurry	7	80	350	58

Source: [17,18].

outlined in Table 2. The proximity is usually determined on site, thus, in the regional-scale study, this serves only as an example.

Apart from the exclusive constraints, the selective criterion influencing the technical and economic viability of projects was defined. In the process of selecting development zones, access to the power network or the natural gas grid play a crucial role, thus, the buffer zones of 2 km intimated by [10] were established to determine the preferential zones.

The digital map layers at a scale 1:750,000 representing the land use (transport infrastructure, wetlands, forestlands, settlement areas), land functions (residential, nature conservation) and nature hazards like floodplains outlined in Table 2 were obtained from the Office of Spatial Planning of the Kujawsko-Pomorskie Voivodeship [24]. In addition, the digital data representing the road and railway infrastructure and build-up areas were complemented by the Corine Land Cover 2006 (1:100,000) data and the Open Street Map (1:50,000) [22,23].

The spatially referenced vector layers were processed using the tools from the Extract, Overlay, Proximity toolboxes in order to produce a map illustrating restricted areas for biogas development (Fig. 2) and to determine optimal zones (Fig. 3). Then both layers were overlapped to extract a final layer of preferred development zones without precluded areas.

The assessment carried out on the regional scale allowed only for a preliminary selection of preferred zones and not for the actual biogas plant planning, since digital data on the high voltage transmission line and the high pressure gas grid was available and because of different scales of the digital datasets, small scattered settlements units, smaller forestland, wetlands and local roads were not taken into account in the analysis.

Table 2
Exclusive and selective criteria for biogas infrastructure development sites.

	Distance/condition
Exclusive criteria	
Forest	–
Water bodies	50 m
Floodplains	50 m
Water protected zones	–
Natura 2000 network, ecological corridors, landscape parks and areas, nature reserves,	–
Built-up areas	300 m
Roads, railways	10 m
Selective criteria	
Power grid	2 km
Gas grid	2 km

Source: [22–24].

2.3. *Site selection based on animal waste*

In the next step, biogas feedstock sources were included in the modelling to determine suitable locations for biogas plants siting inside those development zones. Due to the economies of scale, anaerobic digesters are in the practice located close to large animal farms with at least 100 livestock units (LSU) or inside a cluster of farms [16,25].

In this case study only the cattle and pig population was considered, since they compose 98% of animal live stock units (LSU) [26]. The database with the location of animal farms and livestock populations obtained from the Agency for Restructuring and Modernisation of Agriculture [27] was further geocoded through the website BatchGeo [28] to produce spatially related data on the animal farms and consequently the animal manure.

Table 3
Cattle and pig populations in 2009 and farm waste in the Kujawsko-Pomorskie Voivodship.

	Total population of			Population of more than 100 LSU		
	Population	LSU	Number of farms	Number of farms	LSU	Total manure [t/y]
Cattle	487, 157	389,726	31,617	215	48,074	721,110
Pigs	2, 022, 977	303,447	41,754	317	96,290	1,348,060

Average live stock unit LSU of animal species is an equivalent of 0.8 LSU for cattle unit and 0.15 for pig [26,30] Source: [27].

As small farms predominate in the region, 215 dairy farms and 317 pig farms operated with 100 and more livestock units were taken into account in the analysis as outlined in Table 3.

The collectable amount of animal by-products depends on the size and the structure of animal farms as well as the housing period. With respect to those aspects studied in literature [18,29,30] the biogas yield was calculated based on characteristics outlined in Table 1 and under the assumption that cattle produce 15 tonnes of manure per LSU and pigs 14 tonnes per LSU annually.

The transport distance, over which biogas feedstock can be economically moved, depends on its energy density [5]. In practice, the transportation distances vary from 10 km for liquid manure to 40 km for other agricultural feedstock with dry matter <70% [5,16,31]. As many livestock farms may be located in the near vicinity, the spatial density of the animal manure was calculated within a 10 km distance from each farm. Having explored the manure density (Fig. 4) using the Focal Statistic-sum tool in the Spatial Analyst toolbox, the first site characterised by maximum animal waste density was identified, taking into account the development zones. Then the buffer of 10 km was computed to select associated farms within its area. The selection was an iterative process, so that the map of manure density was computed each time after extracting the cluster of farms. Once the density of animal by-products was lower than an equivalent of 200,000 m^3/y of biogas the iterative processed was interrupted. In the GIS-based modelling, 41 potential sites for biogas plant constructions were identified as illustrated in Fig. 5.

The aim of the first two steps was to identify the suitable sites for biogas development under infrastructural framework conditions and the animal manure supply potential. In practice, manure is collected from one or a several farms. In this study, the biogas potential was estimated based on the manure quantities identified within 41 buffers.

2.4. Evaluation of arable land and agricultural feedstock for biogas generation

The availability of energy crops play a secondary role in determining the location of ADs under assumptions outlined above. In this phase, the arable land and production of selected crops were mapped within areas of 5, 10 and 20 km radiuses from AD sites as illustrated in Fig. 6. The grid cells dedicated to the arable land were extracted from the Corine Land Cover (CLC2006) data representing 44 different land cover classes. The grid format with 100 m cell size was obtained from the EEA [23].

Assuming an average yield of 35 t/ha of crop silage, a potential area of 22,000 ha is required for feedstock planting, which is twice as much as the area of land set aside [26]. With respect to the total area of arable land in the case study region, 2.2% of the area could meet the demand for co-substrates production. The above mentioned document [2] indicates that 700,000 ha of farmland could be intended to grow biogas dedicated crops without harming the food and fodder supply. Since, the fermentation process is based primarily on animal waste, the planting of necessary agricultural co-substrates requires 3% of the total national potential of the farmland.

Having computed the fraction of required land for energy crop planting in the total arable land within three different ranges from

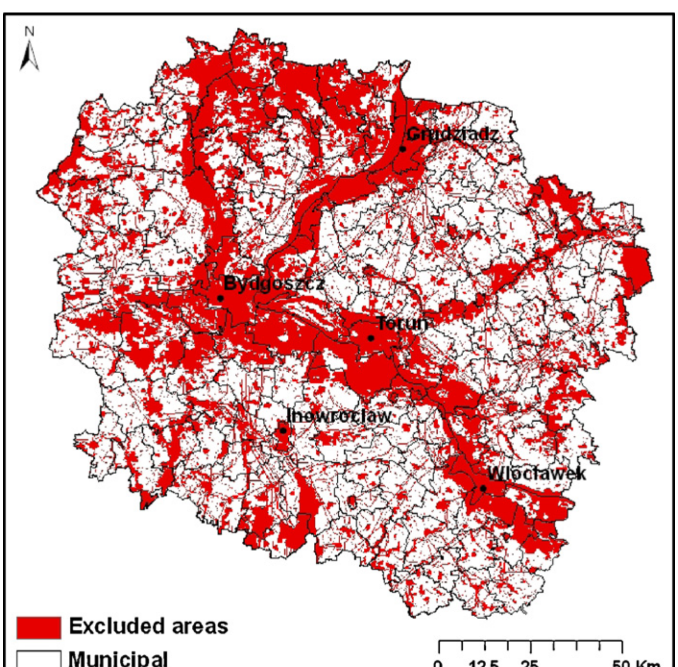

Fig. 2. Excluded areas.

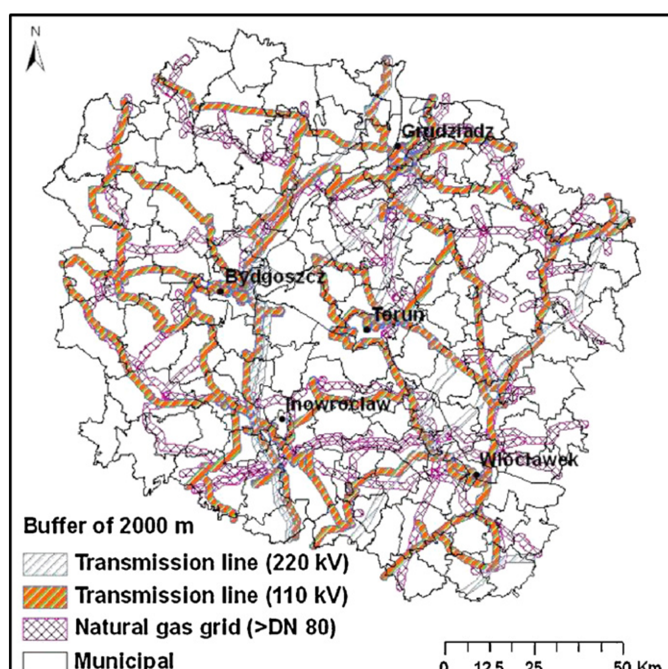

Fig. 3. Buffer of 2000 m around the transmission line and natural gas grid.

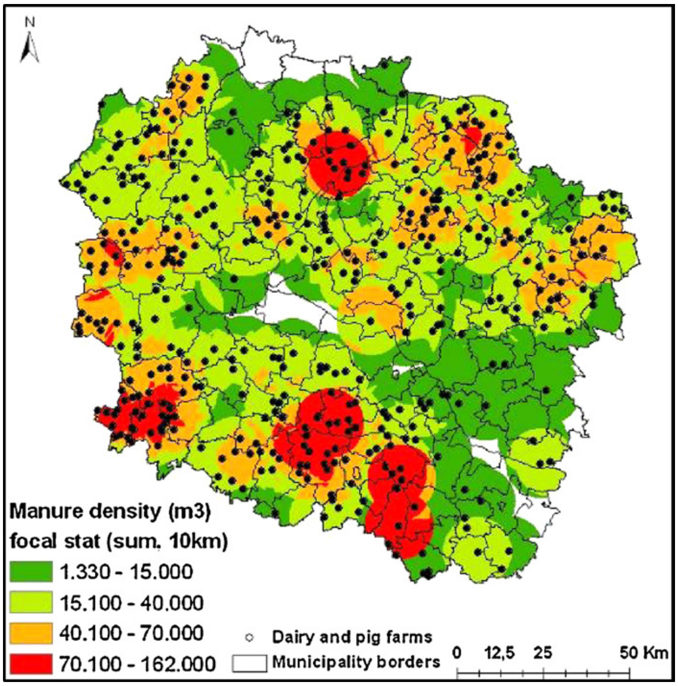

Fig. 4. Focal density of accumulated sum of liquid manure within 10 km radius.

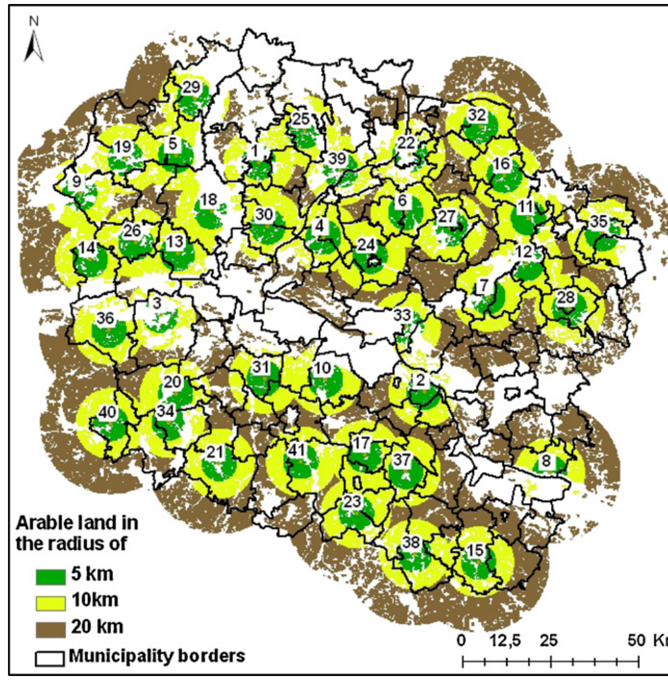

Fig. 6. The arable land in the distance of 5 and 10 and 20 km from potential biogas plants.

biogas plants, outcomes indicated the sufficient area, even in the distance of 5 km from each biogas plant. As shown in Fig. 7 in three cases (sites: 22, 33, 39 on the *x*-axis), the demand exceeds 30% of the land.

The insight into the theoretical potential of arable land provided in Fig. 7 is supplemented by mapping of an area in each circle of 10 km and 20 km radiuses overlapping each other as shown in Fig. 6. By extending distances from biogas plants, the potential of arable land increases, but on the other hand, so does the competition for farmland for energy-dedicated crops growth.

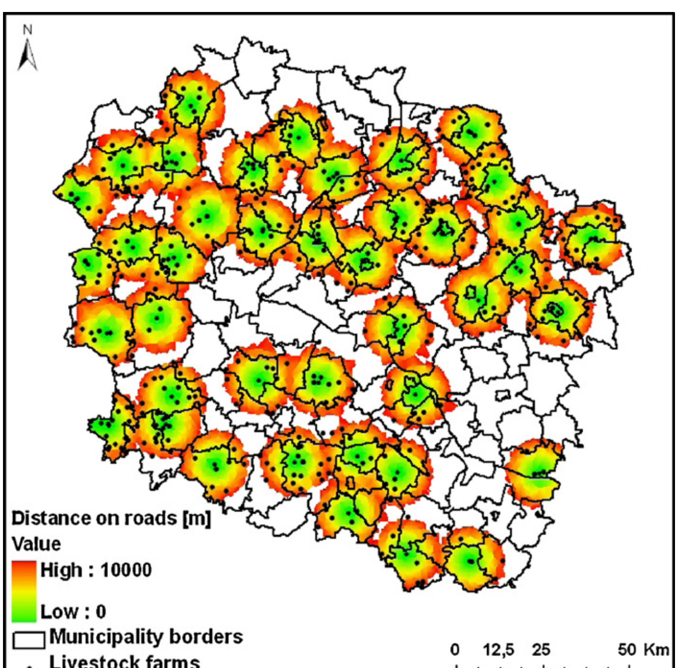

Fig. 5. Selected livestock farms in a distance of 10 km on roads from potential suitable site for biogas development.

In the next phase, the analysis was extended to crop production. The information on the annual production and the grown area at the municipal level was derived from the Agricultural Census [32]. As the data is not detailed enough to map the spatial deployment of crop yield in three different ranges, the data on annual yields of maize, wheat and rye (Table 4) was disaggregated uniformly onto the cells of the arable land of CLC2006 at the grid of 100 m × 100 m according the formula:

$$CY_i = \frac{\text{CYa}}{\sum \text{ALCLCa}} \quad [\text{t}] \tag{2}$$

where CY_i is the annual crop yield in the grid mesh of 100 m × 100 m [t/ha], CYa is the total crop yield per administrative unit a [t/a*y], ALCLCa is the sum of cells of arable land class of Corine Land Cover raster within each municipal unit.

The total quantity of the fresh mass of selected crops cultivated was calculated from the planting area of crops multiplied by the yield of fresh mass reported by [13,14] as outlined in Table 4.

The quantity of agricultural feedstock such as maize, wheat and rye silage was calculated within distances of both 5 and 10 km as presented in Figs. 8 and 9. In the 5 km radius the quantity of selected crop hardly meets the demand for crops (green line) at sites such as 9, 22, 33, 35 and 41. (For interpretation of the references to color in this text, the reader is referred to the web version of the article.) Extending the radius up to 10 km (Fig. 9), the required amount of co-substrates can be covered just by maize at most sites.

Addressing the overlapping farmland within a range of 10 km, Fig. 10 illustrates the share of crop production computed in the adjacent circle. For instance, at the site numbered 34, more than 50%

Table 4
Agricultural feedstock quantity [t_{fm}/y].

Crops	Yield [t_{fm}/ha]	Grown area [ha]	CYa [t_{fm}/y]
Maize	30–50	85,688	3,427,520
Wheat	30–50	192,868	7,714,720
Rye	30–35	76,804	2,688,140

Source: [32,33].

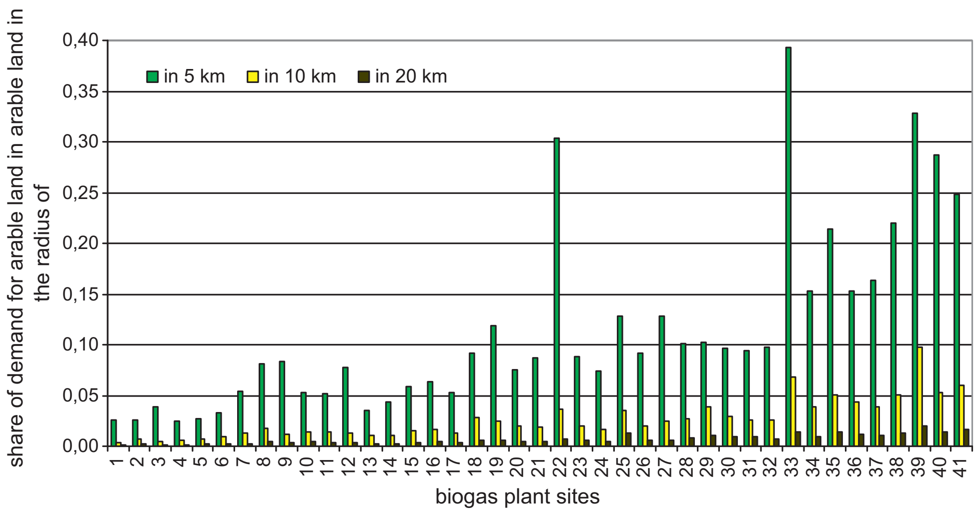

Fig. 7. The ratio of required arable land for feedstock planting to arable land in the range of 5 and 10 and 20 km from potential biogas plants.

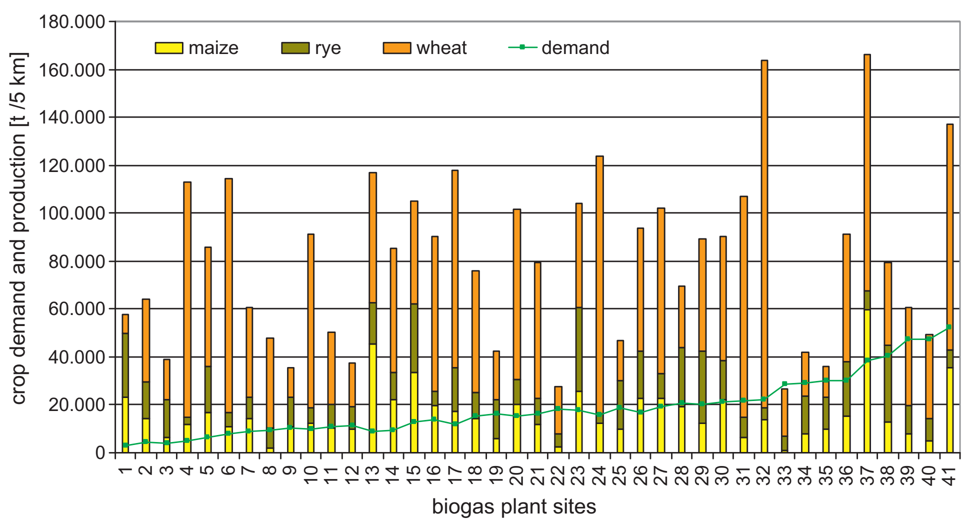

Fig. 8. Crop requirement and production within 5 km range of biogas plants.

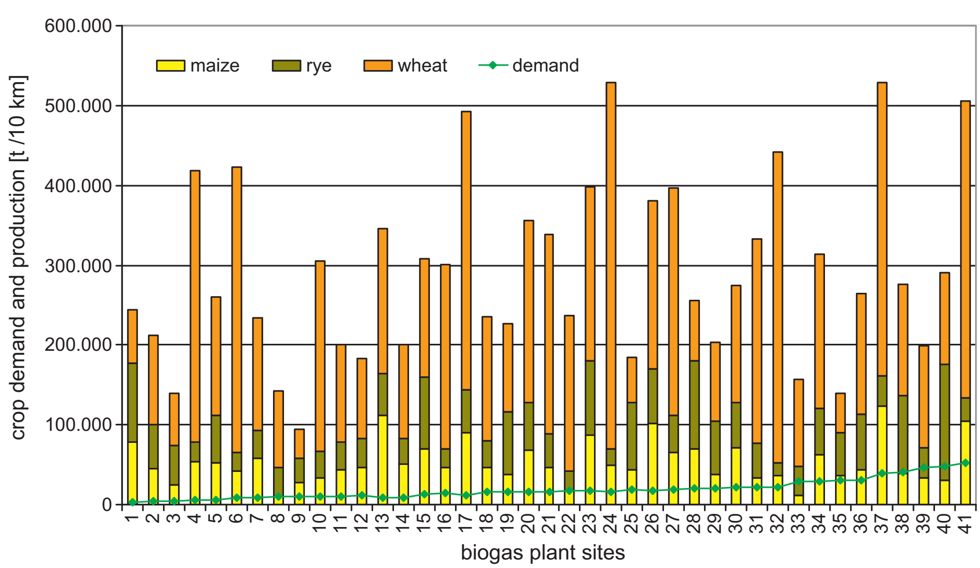

Fig. 9. Crop requirement and production within 10 km range of biogas plants.

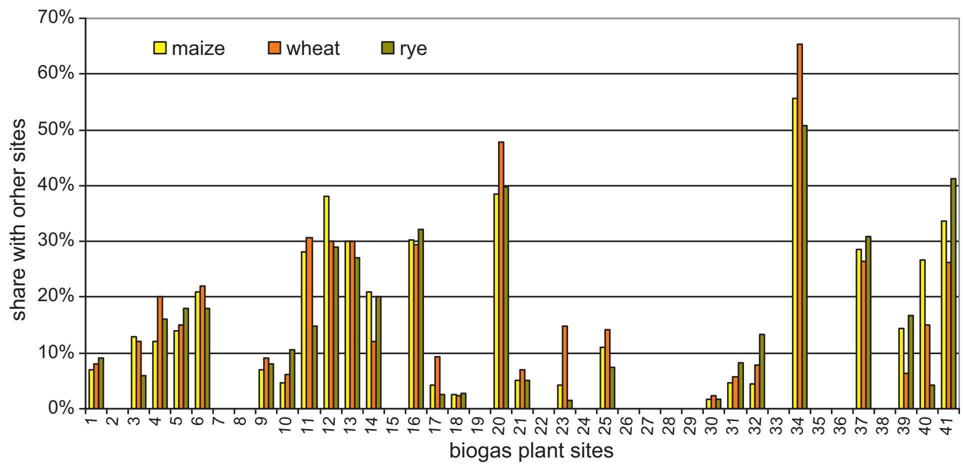

Fig. 10. Overlapping ranges of crop production within a distance of 10 km from biogas plant sites.

of maize, wheat and rye yield was cultivated within a 10 km area of biogas plants numbered 40, 20 and 21 (compare Figs. 6 and 10).

Due to crop rotation constraints,[1] patterns of crop cultivation change from year to year and it is impossible to predict over the following years the site and area of crop plantations. Therefore, the exemplary results of crop production based on the historical data may fluctuate over time. Nevertheless, this approach provides insight into the structure of agricultural production and indicates the theoretical potential of farmland for crop planting in terms of distance from biogas sites but also takes into account the possible competition for the arable land and crop resources.

2.5. Transportation costs of biogas feedstock

Due to the low energy content of liquid manure and its distributed sources the GIS model was developed to determine the on-road distance and the cost of manure transportation. Firstly, the road network derived from [22] was rasterised at a grid of 25 m × 25 m using the tool Polygon to Raster and then two continuous grids of distance and transportation costs to each potential biogas plant sites were computed using functions of Euclidean distance and Euclidean allocation from the Spatial Analyst in the ArcGIS 9.3. Then using the Single Output Map Algebra the unit delivered costs at 0.024 €cents/m^3*m [34] were multiplied by the quantity of manure at animal farms and appropriate distance to estimate the total cost of animal waste delivered to biogas plants.

The transportation cost of agricultural co-substrates was not calculated as for the manure, since the spatial deployment of particular parcels for crop planting was not appointed.

2.6. Energy production from biogas

The assessment of technical potential dealt with the energy generated either in CHP plants or bio-methane production fed into the gas grid. The electrical power output for CHPs was plotted against the hourly biogas flow from anaerobic digesters according to data derived from [10] as follows:

$$\text{Electrical power [kWe]} = 1.8543 \times \text{biogas flow}\,[\text{m}^3/\text{h}] \quad (3)$$

A basic parameter for calculating the electricity and heat generation in CHP units is the scale-dependent energy conversion efficiency [35]. The efficiency trend of electricity and heat conversion was studied on the basis of the data provided by literature [17] and [10] and fitted by power regression function as follows:

$$\text{Electricity efficiency [\%]} = 19.02 \times \text{el. power output [kWe]}^{0.10} \quad (4)$$

$$\text{Heat efficiency [\%]} = 50,998\ \exp(0.0002 \times \text{el. power output [kWe]}) \quad (5)$$

On this basis, electricity and heat were estimated by multiplying the efficiency factors by the gross energy.

In the case of methane injection into the gas grid, the biomethane (m^3/y) generated in 41 potential ADs was converted to the electricity equivalent. The Energy Law revised on 8th January 2010 introduced the agricultural biogas certificate of origin, which will be implemented on the market from the 1st of January 2011 to support the production of bio-methane fed into the natural gas grid [36]. However, there is no ordinance, which regulates the calculation method for recalculating the bio-methane into the equivalent electrical energy and the purchase price of the certificate is still unknown. Therefore, the amount of electricity was calculated under the assumption that 9.7 MWh is the equivalent of one cubic meter of the upgraded methane. The results of technical assessment are outlined in Table 5.

2.7. Costs-benefit analysis

The economic analysis was carried out to provide insight into the structure of cost and benefits as well as to examine what incentive measures cover the biogas generation costs. Considering the economic feasibility of feeding bio-methane into the gas grid, the purchase price of (brown) certificate of origin was discussed. In this paper, the specific investment costs for both technical options were analysed by means of regression functions plotted for the data studied in the literature.

The power regression of best fit data derived from [10,17,37] was used to estimate the investment costs of the AD from the biogas flow as flows:

$$\text{cost}\,[€/\text{m}_\text{n}^3/\text{h}] = 14,239 \times \text{biogas}\,[\text{m}_\text{n}^3/\text{h}]^{-0.2209} \quad (6)$$

In the combined electricity and heat production system, the investment includes the CHP unit costs and the costs of its operation, maintenance and connection to the power grid and to the district heating network.

The investment cost of the gas Otto engine was estimated from the power regression plotted for the data [17], which depicts the

[1] Crop rotation is the practice of growing a series of dissimilar types of crops in the same area in sequential seasons for various benefits such as to avoid a decrease in soil fertility.

Table 5
Estimated potential of the energy generated from substrate-mix, total annual on-roads costs manure from farms to selected potential sites.

Site	LSU	Liquid manure, m^3	Transport costs, k €	Agricultural feedstock, t_{fm}/y	Total methane, ths m^3	Total el. power, kWe	Electricity, MWhe/y	Heat, MWhth/y	Bio-methane equivalent of electrical energy, MWh/y
1	2328	9374	10	3192	440	183	1465	2159	4271
2	3528	11,428	19	4374	574	237	1959	2782	5563
3	2461	13,395	15	3955	583	241	1995	2826	5657
4	2527	20,355	28	5161	822	338	2907	3906	7971
5	4081	20,807	17	6324	920	378	3290	4337	8920
6	7467	16,978	15	8057	970	398	3490	4557	9413
7	8602	18,064	30	9032	1067	438	3876	4974	10,354
8	8663	20,786	12	9528	1163	477	4257	5375	11,277
9	9312	21,654	22	10,127	1226	503	4515	5641	11,896
10	7367	27,529	26	9745	1321	541	4901	6031	12,817
11	9093	25,867	39	10,676	1357	556	5046	6176	13,163
12	10,182	24,352	24	11,186	1364	558	5074	6203	13,229
13	4956	33,574	38	9065	1397	572	5211	6338	13,553
14	4877	35,863	35	9391	1470	602	5511	6630	14,262
15	11,164	30,038	15	12,821	1608	658	6081	7170	15,598
16	11,716	34,751	59	13,993	1797	734	6870	7889	17,426
17	6483	44,611	80	11,973	1851	757	6624	8092	17,956
18	13,951	33,782	53	15,396	1883	769	6748	8866	18,262
19	13,042	41,417	64	16,032	2092	855	7578	9768	20,293
20	11,375	45,024	62	15,467	2125	868	7710	9910	20,615
21	12,798	43,082	41	16,139	2135	872	7751	9953	20,713
22	16,742	37,792	41	18,018	2166	885	7875	10,085	21,015
23	15,166	41,402	76	17,517	2205	900	8027	10,247	21,384
24	11,488	47,677	86	15,988	2221	907	8092	10,315	21,542
25	16,682	41,972	66	18,673	2304	941	8428	10,667	22,353
26	12,092	50,460	80	16,874	2347	958	8599	10,845	22,765
27	16,230	48,577	87	19,457	2503	1022	9231	11,495	24,283
28	17,797	48,531	60	20,546	2585	1055	9564	11,831	25,076
29	16,433	51,448	83	20,078	2611	1066	9669	11,937	25,328
30	17,968	53,009	79	21,412	2745	1120	10,218	12,483	26,631
31	18,889	52,200	97	21,922	2767	1129	10,307	12,571	26,842
32	17,610	58,781	92	22,124	2921	1192	10,940	13,188	28,337
33	26,767	59,418	113	28,640	3430	1402	13,055	15,161	33,270
34	25,519	66,688	77	28,978	3609	1475	13,806	15,837	35,007
35	26,671	69,137	113	30,192	3753	1534	14,413	16,372	36,403
36	25,325	74,220	122	30,098	3853	1575	14,836	16,741	37,374
37	34,175	88,033	107	38,595	4790	1956	18,099	21,384	46,464
38	36,537	88,152	127	40,268	4920	2008	18,639	21,885	47,721
39	43,821	99,172	52	47,203	5679	2317	21,826	24,749	55,088
40	43,800	99,999	75	47,327	5706	2328	21,939	24,848	55,348
41	40,615	142,949	265	52,255	6987	2849	27,412	29,387	67,773
Total	646,300	1,892,345	2604	767,801	98,270	40,155	367,835	441,611	953,215

correlation of the electrical power output with specific investment costs as:

$$\text{cost}\,[€/\text{kWe}] = 3814.8\,(\text{el. power output})^{-0.2916} \tag{7}$$

The operation and maintenance costs associated with feeding, operating and repairing the plant, storage and disposal of the substrates and administration were defined as a constant and size-independent fraction of investment costs 0.04 for an anaerobic digester and 0.03 for CHP [15].

Additional costs of bio-methane clearing (removing hydrogen sulphide, because of its highly corrosive nature and odour) were included in the economic assessment according to the costs studied by [10]. Depending on the biogas flow, the unit cost of desulphurisation was calculated from the lognormal function as follow:

$$\text{cost}\,[€\text{cents}/\text{m}_\text{n}^3] = -0.9282 \times \ln(\text{biogas}\,[\text{m}_\text{n}^3/\text{h}]) + 6.4625 \tag{8}$$

Estimating the costs of biogas upgrading technologies is more speculative than for AD and CHP equipment, since several upgrading plants are operated at agricultural biogas plants in Sweden and Germany [38], but in Poland there has been so far no such installation. Based on costs for major biogas upgrading technologies collected by [10] the regression function was plotted for two exemplary technologies:

a) for water wash technology:

$$\text{cost}\,[€/\text{m}_\text{n}^3] = 233,666 \times \text{biogas}\,[\text{m}_\text{n}^3/h]^{-0.4723} \tag{9}$$

b) for pressure swing adsorption technology:

$$\text{cost}\,[€/\text{m}_\text{n}^3] = 7648.3\,(\text{el. power output})^{-0.9714} \tag{10}$$

The annual operation and maintenance cost of the water wash technique was considered in the calculation as a fixed fraction of 8% of investment costs and the pressure swing adsorption technologies of 12% of investment costs respectively.

Since the costs of the connection to the gas grid or the power network and the district heating network are difficult to estimate without the site specific information, the fix expenditure were adopted after [10].

Significant parameters affecting project profitability are the cost of substrates acquisitions [39]. Purchase prices for maize silage vary between 17 €/t and 25 €/t and cereals silage between 20 and 30 €/t [40]. In this study the transportation costs of agricultural feedstock were included in the purchase price. The farm manure is available mainly at the costs of transport only, which varies between 1.2 €/m^3 and 1.5 €/m^3 for a distance of 5 km, depending on the type of means of transport, for a 10 km distance these costs double [34]. The model for calculating the mobilisation costs of farm manure

was discussed in chapter 2.5. However, the costs of animal waste collected from external farms may amount to 10 €/t [40,41], which price option was included in the cost–benefit analysis.Additionally, one should include the cost of digester utilisation at 3 €/t [42]. Moreover, according to [43] the digested material from the agricultural biogas plant, which is classified as the industrial production, cannot be directly returned to farms for land application. Each biogas plant utilising the waste from the food and agricultural sector is obliged to acquire a certificate permitting for the digester allowing its further reuse. Nevertheless, document [2] indicates a change in this legal provision to facilitate direct utilisation of this material.

The annual cost of energy generation was estimated from components of the investment cost annualised over the economic lifetime of the plant. The sum of different costs under financial parameters changed in the economic (sensitivity) analysis was divided by the sum of annual production of electrical and heat energy as follow:

$$C_n = \frac{C(m + Cf + Cc + OM + A + I_0 \times s \times a)}{Ee + Eh} \quad [€/\mathrm{MWh}] \tag{11}$$

$$a = \frac{i(1+i)^n}{(1+i)^{n-1}} \tag{12}$$

where C_n is the production cost of energy (electricity and heat or gas), Cm is the mobilisation cost of feedstock, Cf is the cost of biogas feedstock, Cc is the connection costs, I_0 is the sum of investment costs of anaerobic digester, CHP or upgrading techniques, s is the subsidy to the qualified costs, a is the annualised rate, Ee and Eh is the annual electrical and heat energy generated, OM is the annual operating cost, A is the amortisation, i is the interest rate (%), n is the economic life time of the plant.

A lifetime of 20 years was assumed for the entire equipment and an average amortisation rate of 8% of investment costs over a period of 15 years. The annuity factor was calculated over 15 years at 4% of interest rate. The energy unit cost was derived from different fraction of costs summed up over the 20 years and divided by 20.

The revenue earned from the production of electricity and heat is composed of the market price of electricity and heat as well as the price of the tradable set of certificates of origin extended by the legal framework in recent times. The unit revenues per energy generated were calculated as:

$$Re = \frac{(En \times PE + Hn \times PH + (En + En \times 0.09) \times Pcg + Ee \times Pcyv)}{Ee + Eh} \quad [€/\mathrm{MWh}] \tag{13}$$

where En is the net energy fed into the power grid, Hn is the purchase price of net heat. It is assumed that around 9% of electricity and 25–40% of the heat is used for processes related to the biogas production [17,40].

In 2010, the minimum sale price for the electricity of 45 € for each MWh[2] was guaranteed by the Energy Regulatory Office. Feeding heat into the local district heating network, producers can increase their incomes by 8 €/GJ (2.3 €/MWh) [1].

Besides, producers of green electricity also acquire a green certificate (Pcg) that can be traded for 68 €/MWh[3] calculated from the gross electrical energy generated. Since the amendment to the Energy Law from 1st of March 2010, the additional source of benefits – the yellow certificates can be joined with the green certificate. These certificates of origin are received for the electricity generated in the high-efficiency cogeneration (at least 75% overall efficiency) regardless the power capacity in case of the agricultural biogas. Moreover, the new violet certificate of origin for electricity produced from the bio-methane (and methane from dump sites and coal mines) in high-efficiency cogeneration was introduced on August, 9 2010 and can be used interchangeably with yellow certificate in biogas plants. The market regulator (URE) sets the reference price of certificates for each year within a fixed range determined in the Energy Law. In 2010 the purchase price of yellow certificates was 30 € per MWh [44] and violet ones was 14.8 € per MWh, which price was also fixed for 2011.

One should note that both co-generation incentive schemes are applied only if the heat generated is used in a great part for personal purposes or purchase on the market.

As mentioned in the previous section, the amendment to the Energy Law from 8th January 2010 promotes not only the biogas-based combined electricity and heat production but also bio-methane feeding into the natural gas grid. The system of certificates of origin (brown) will be implemented on the market from the 1st January 2011 [45].

So far, the reference price of the violet certificate is unknown, thus, the unit revenue from methane injection into the gas grid (Rm) was calculated as follows:

$$Rm = Em \times \frac{Pm}{Em} \quad [€/\mathrm{MWh}] \tag{14}$$

where Em is the equivalent of bio-methane expressed in MWh (assuming that one cubic mater of upgraded methane is equal to 9.7 kWh), Pm is the price for natural gas calculated without distribution costs, which was 25 €cent/m^3 (2.6 €cents/kWh).

2.8. Results of the techno-economic analysis

Table 5 outlines the results of the analysis discussed in the previous sections: the amount of animal manure estimated its summarised on-road transportation costs, the amount of agricultural co-substrates as well as the electrical power output and energy generation. 41 biogas plant could exploits 1.9 Mm^3 of farm waste, which composes 92% of the considered amount of manure from animal farms housing at least 100 LSU. Under assumptions made as outlined above, the mass fraction of manure in co-fermentation technologies varies from 67% to 80% and the rest are crop silage. The CHP plants, whose electrical power output varies from 183 kWe up to 2850 kWe, could generate 368 GWh of electricity and 442 GWh of heat. Alternatively, the bio-methane produced in ADs could meet the demand for natural gas in 98 Mm^3.

2.8.1. Costs and revenues from CHP generation

Due to the common problem of the seasonal fluctuation of demand for heat, income structure may vary over the year. As seen in Fig. 11, biogas plants are not profitable, as the annual benefits composed only the purchase price of electricity and green certificates, even if the annual costs were calculated including the transport costs of manure and the lowest price for co-substrates of 20 € per tonne. Increasing the price for cereal silage up to 30 €/t, only a few biogas projects generate incomes from selling electricity, heat as well as green and yellow certificates. The unit costs react much sensitive on the additional price of 10 € per m^3 of manure added to the transpiration costs making the projects totally unprofitable.

Until March 2010 the aid mechanism (the green certificates) benefited the least costly technologies like the wind turbines, the quota-based mechanism has been diversified to support relatively expensive biogas projects. However, as seen in Fig. 11, the set of certificates by itself is still not sufficient to drive biogas development under the upper level of feedstock prices.

Additionally, a high investment risk is associated with income uncertainty over the lifetime of the technology, as the yellow certificate scheme is guaranteed only until 2012, after which

[2] The electricity sale price is equivalent to the median market price during the previous sales year.

[3] The median price in the beginning of the year 2010.

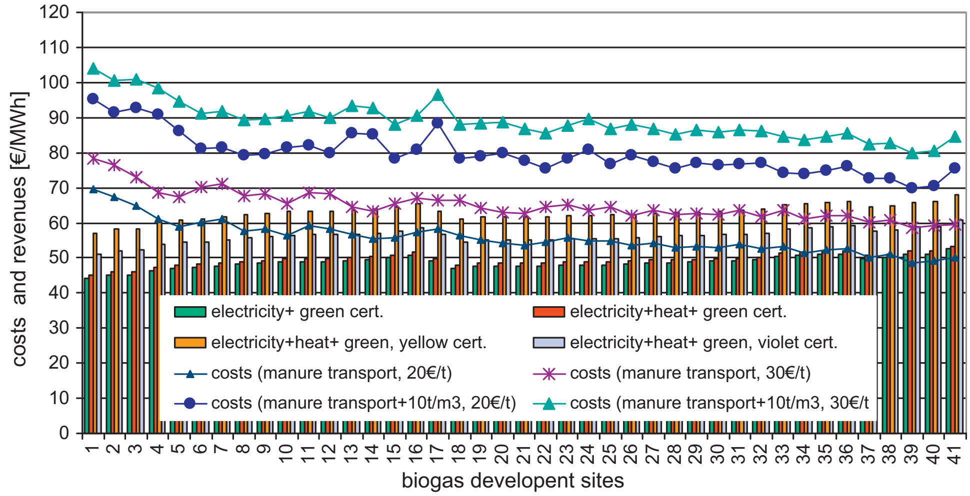

Fig. 11. Annual incomes from four sources (columns) and costs depending on the biogas feedstock costs of acquisition. Annuity factor calculated over 15 years at 4% of interest rate.

the government will review their impact on the market and decide whether to continue the scheme. Therefore, the violet ones securing the income until 2018 were introduced, but their purchase price is less than half as much as the yellow. The mechanism scheme of green certificates was prolonged from 2014 until 2017.

Therefore, to improve the still challenging economic and political conditions for development of the biogas industry in Poland, apart from preferential loans and energy tax incentives, various forms of funded subsidies from regional, national and European sources have been recently launched and many are planned [2,45]. In the most optimistic cases subsidies up to 70% of qualified costs can be granted, but on average 50%.

Assuming a subsidy of 50% to the investment in AD and CHP equipment, the total annual unit costs of energy generation were plotted against the same level of revenues as shown in Fig. 12. In this case, plants of 2 MW and more generate benefits even without purchasing the certificates but under the lowest level of biogas feedstock acquisition prices.

The calculation carried out for both options with and without grants show that the economic viability depends mostly on acquisition costs of the biogas feedstock. In addition, without the co-generation certificate support (yellow or violet), which can be obtained simultaneously with the green certificate from March 2010, most of biogas projects would be unprofitable, even with grant of 50% to eligible costs.

2.8.2. Costs and revenues from the bio-methane grid injection

This section presents the results from the cost–benefit analysis carried out for the more efficient alternative of the bio-methane utilisation over a whole year. The unit costs of the bio-methane grid injection were plotted for different costs of feedstock and both options with and without subsidies. As shown in Fig. 13, the average price of 27 €/MWh (0.25 €/m^3) offered for the natural gas without distribution fees, taxes does not meet the unit costs of bio-methane production. Even the preferential interest rate of 4% and 50% of subsidy to the anaerobic digester as well as to both upgrading technologies; water wash (WW) and pressure swing adsorption (PSA) does not suffice to generate benefits.

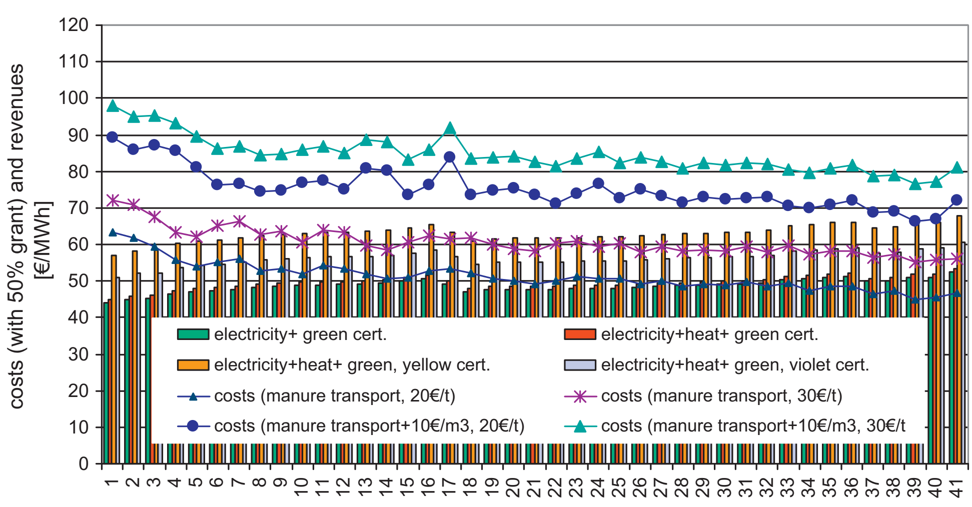

Fig. 12. Annual incomes from four sources (columns) and costs depending on the biogas feedstock costs of acquisition. Annuity over 15 years at 4% interest and 50% of subsidy.

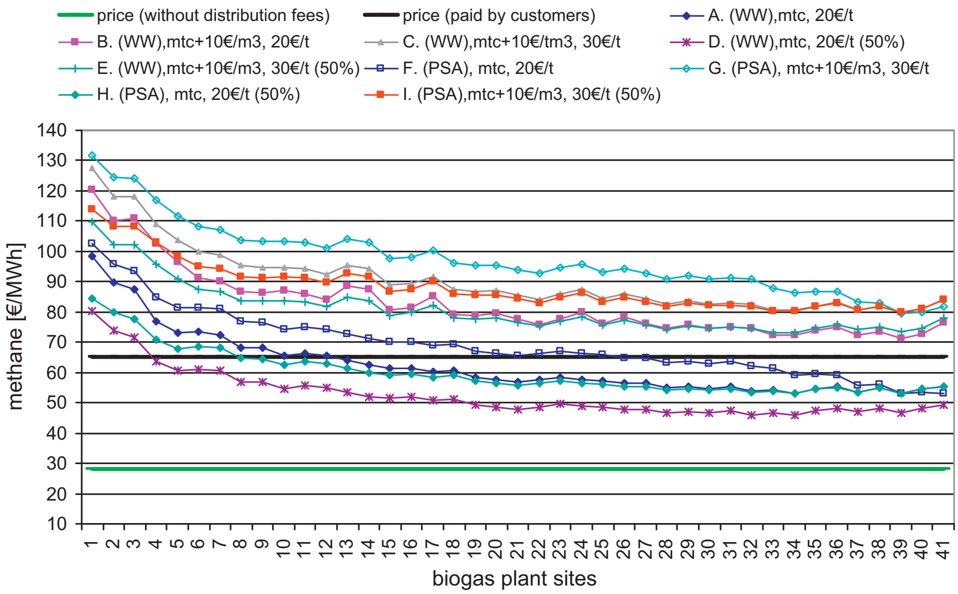

Fig. 13. Costs of methane production calculated under different feedstock costs for the water wash (WW) and the pressure swing adsorption (PSA) upgrading technologies with interest rate of 4% (over 15 years of financing period) and interest rate at 4% and subsidy at 50% to the investment. *Explanation*: mtc, manure transportation costs; (50%), grant; WWW and PSA, upgrading technologies.

Therefore, the brown certificates of origin are necessary to compensate the gap between costs and revenues as well as investment risks related mostly to the costs of feedstock supply.

Since the average costs varies from 50 € up to 90 € per MWh, the minimum certificate purchase price of 23 €/MWh should be guaranteed, and the maximum of 63 €/MWh – the current price of the green certificate.

3. Conclusion

The method developed in the GIS environment provides the support tool that allows for determining the suitable locations for the biogas development. The GIS-based site selection procedure optimises the AD distribution taking into spatial components among others the proximity to the infrastructure and spatial density of the biogas feedstock availability that influence the technical and economic feasibility of the biogas production. Besides, the potential negative impact on the social and ecological systems can be evaluated by taking into account the GIS modelling the restrictions for AD siting.

The GIS is also a useful means for calculating distances and transpiration costs of animal manure while colleting from different animal farms. Moreover, its flexibility allows for including different spatial and non-spatial data (i.a. investment costs, transportation costs) that quantify the techno-economic biogas potential.

The application of the methodology in the case study showed the considerable potential for biogas production that could meet the demand for 368 GWh of electricity and 442 GWh of heat or 98 Mm^3 of methane (5% of the target) based on assumed biogas feedstock mix. The quantity of biogas, which could contribute to the energy supply, depends not only on the availability of agricultural resources and on infrastructural conditions but to a great extent on the legal framework and financial aid scheme. Therefore, the paper highlights the recent course of changes in legal regulations and incentive measures, which significantly contribute to technical and financial feasibility of biogas projects, especially plants of electrical capacity output greater than 300 MWe, which, from an economic point of view, are much more profitable than smaller units.

On the other hand, the paper points out that the main investment risks producers face, which is associated with unforeseen income sources like certificate mechanisms that have been not guaranteed over the entire lifetime of biogas plants. The time limit for issuing certificates should be abolished if the government aims to increase biogas power from its current 77 MWe to 2500–3000 MWe.

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References

[1] URE, Sprawozdanie z działalności Prezesa URE – 2009 (Report of the Energy Regulatory Office). Biuletyn Urzedu Regulacji Energetyki. Warszawa: Urząd Regulacji Energetyki; 2010 [Energy Regulatory Office].
[2] Ministry of Economy. Kierunki rozwoju biogazowni rolniczych w Polsce w latach 2010–2020 [Development of agricultural biogas plants in Poland in years 2010–2020 adopted on 13th July 2010]. Warsaw: Ministry of Economy, Editor; 2010.
[3] Ma J, Scott NR, DeGloria SD, Lembo AJ. Siting analysis of farm-based centralized anaerobic digester systems for distributed generation using GIS. Biomass and Bioenergy 2005;28:591–600, doi:10.1016/j.biombioe.2004.12.003.
[4] Plata A. Optimale Standorte von Biogasanlagen. Geographische Informationssysteme als entscheidungsunterstützende Instrumente im Bereich Bioenergie. Standort – Zeitschrift für Angewandte Geographie 2008;32:141–6.
[5] Dagnall S, Hill J, Pegg D. Resource mapping and analysis of farm livestock manures—assessing the opportunities for biomass-to-energy schemes. Bioresource Technology 2000;71:225–34.
[6] Batzias FA, Sidiras DK, Spyrou EK. Evaluating livestock manures for biogasnext term production: a GIS based method. Renewable Energy 2004;30:1161–76.
[7] Gómez A, Zubizarreta J, Rodrigues M, Dopazo C, Fueyo N. An estimation of the energy potentialnext term of agro-industrial residues in Spain. Resources, Conservation and Recycling 2010;54(11):972–84.
[8] White AJ, Kirk DW, Graydon JW. Analysis of small-scale biogasnext term utilization systems on Ontario cattle farms. Renewable Energy 2011;36(3):1019–25.
[9] Leible L, Arlt A, Fürniß B, Kälber S, Kappler G, Lange S, et al. Energie aus biogenen Rest- und Abfallstoffen. Bereitstellung und energetische Nutzung organischer Rest- und Abfallstoffe sowie Nebenprodukte als Einkommensalternative

für die Land- und Forstwirtschaft-Möglichkeiten, Chancen und Ziele, FKid Helmholtz-Gemeinschaft. Editor. Karlsruhe: Forschungszentrum Karlsruhe in der Helmholtz-Gemeinschaft; 2003. p. 300.
[10] Urban W, Lohmann H, Girod K. Technologien und Kosten der Biogasaufbereitung und Einspeisung in das Erdgasnetz. Ergebnisse der Markterhebung 2007–2008. Oberhausen, Leipzig, Wuppertal, Trier: Fraunhofer-Institut für Umwelt-, Sicherheits- und Energietechnik; 2009. p. 124.
[11] Braun R. Anaerobic digestion: a multi-faceted process for energy, environmental management and rural development. In: Improvement of crop plants for industrial end uses. Netherlands: Springer; 2007.
[12] Braun R, Weiland P, Wellinger A. Biogas from energy crop digestion. I Bioenergy; 2009.
[13] Michalski T. Z pola dla przemysłu. Kukurydza rośliną przyszłości. Poradnik dla producentów, in Agro Serwis 2005:7–13.
[14] Podkówka W. Kiszonka z kukurydzy wartościowa pasza i cenny surowiec do produkcji biogazu (Corn silage – valuable fodder and raw material for biogas production). Kukurydza 2006;3(29):40.
[15] DBFZ. Monitoring zur Wirkung des Erneuerbare-Energien-Gesetzes (EEG) auf die Entwicklung der Stromerzeugung aus Biomasse. Zwischenbericht "Entwicklung der Stromerzeugung aus Biomasse 2008". Deutsches Biomasse-ForschungsZentrum (DBFZ); 2009.
[16] FNR. Wege zum Bioenergiedorf. Leitfaden für eine eigenständige Wärme- und Stromversorgung auf Basis von Biomasse im ländlichen Raum. Gülzow: Fachagentur Nachwachsende Rohstoffe e.V. (FNR); 2009.
[17] FNR. Handreichung Biogasgewinnung und -nutzung. Gülzow: Fachagentur Nachwachsende Rohstoffe:; 2006.
[18] Schulz H, Eder B. Biogas Praxis, Grundlagen, Planung, Anlagenbau. Freiburg: Ökobuch; 2001.
[19] Weiland P. Biogas production: current state and perspectives. Microbiol Biotechnology 2010;85:849–60, doi:10.1007/s00253-009-2246-7.
[20] Laursen B. Biogazownie rolnicze [Biogas plants in agriculture]. In: Biogazownie rolnicze. Polandor: Przechlewo; 2009. p. 14.10.2009.
[21] Ministry of Environment. Law on Nature Protection Dz.U. z 2004r. Nr 92, poz. 880, z 2005 r. Nr 113, poz. 954, Nr 130, poz.1087, MSMo Environemnt), Editor. Warsaw: Kancelaria Sejmu; 2005.
[22] Geofabrik. Geofabrik – OpenStreetMap at a scale 1: 50000. Online; 2010 [Last access: 21.06.10] http://download.geofabrik.de/osm/europe/.
[23] IGIK. Corine Land Cover data for 2006 at a scale 1: 100 000. The European Environment Agency (EEA), Instytut Geodezji i Kartografii (Institute of Geodesy and Cartography in Poland); 2009.
[24] KPBPP. Digital data for spatial plans (scale 1:750 000). Kujawsko-Pomorskie Biuro Planowania Przestrzennego i Regionalnego we Włocławku, The Regional Spatial Olaning Office in Włocławek; 2009.
[25] ECBREC IEO. The comprehensive assessment of the bio-energy development prospects in Poland. Review of biomass resources and potentials, in Sustainable energy for poland. The role of bioenergy. Warsaw: EC Baltic Renewable Energy Centre ECBREC/IBMER; 2004. p. 80.
[26] GUS. Regional databank. Agricultural data, online. Główny Urząd Statystyczny (Central Statistical Office); 2009 [Last access: 21.04.10] http://www.stat.gov.pl/bdren_n/app/dane_podgrup.katgrupg?p_dane=0&p_kate=34.
[27] ARiMR. Livestock population. Torun: Agencja Restrukturyzacji i Modernizacji Rolnictwa (ARiMR) w Toruniu (The Agency for Restructuring and Modernisation of Agriculture); 2010.
[28] BatchGeo. BatchGeo online: http://www.batchgeo.com/de/ [Last access: 21.06.10].
[29] Steppa M. Biogazownie rolnicze [Agricultural biogas plants]. Warsaw: IBMER; 1992.
[30] MRiRW-MS, IUNG, FAPA. Kodeks Dobrej Praktyki Rolniczej [Good Farming Practice Code]. Warszawa: Ministerstwo Rolnictwa i Rozwoju Wsi (Ministry of Agriculture and Rural Development), Ministerstwo Srodowiska (Ministry of Enironment); 2004. p. 98.
[31] Wuppertal Institut fKUE. Analyse und Bewertung der Nutzungsmöglichkeiten von Biomasse. Wuppertal: Wuppertal Institut für Klima Umwelt Energie; 2006.
[32] GUS. Regional databank. Agricultural census 2002. Główny Urząd Statystyczny (Central Statistical Office); 2009.
[33] GUSB. Rolnictwo w wojewodztwie Kujawsko-Pomorskim w 2008 [Agriculture in Kujawsko-Pmorskie in 2008]. Bydgoszcz: Urząd Statystyczny w Bydgoszczy.(Statistical Office in Bydgoszcz); 2009.
[34] Michalski T. Produkcja biogazu w dużych fermach mlecznych; 2009. Available online: http://www.agrosukces.pl/produkcja_biogazu_w_duzych_fermach_mlecznych,95,agroenergia,artykul.html.
[35] Celma AR, Rojas S, Lopez-Rodrıguez F. Waste-to-energy possibilities for industrial olive and grape by-products in Extremadura. Biomass and Bioenergy 2007;31:522–34.
[36] Ministry of Economy, Ustawa Prawo energetyczne (Act on Energy) (Dz. U. 1997 No. 54, item 348) with ammendments 2005, 2007, 2008, 2010, MoE Affairs, Editor. 1997, 2010. Warsaw: The Council of Ministers.
[37] KTBL. Der Wirtschaftlichkeitsrechner Biogas ist eine Planungshilfe zur Abschätzung der Substratmengen, der Anlagengröße und der Wirtschaftlichkeit. Das Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V.(KTBL); 2010.
[38] Fritsche UR, Hennenberg K, Hünecke K. IEA bioenergy task 40: country report Germany. Leipzig, Darmstadt: DBFZ, Öko-Institut; 2009. p. 58.
[39] Szlachta J, Fugol M. Analiza możliwości produkcji biogazu na bazie gnojowicy oraz kiszonki z kukurydzy. Inzynieria Rolnicza 2009;5:275–80.
[40] MAE. Biogaz rolniczy-produkcja i wykorzystanie [Agricultural biogas production and use]. Warszawa: Mazowiecka Agencja Energetyczna Sp.z o.o.; 2009.
[41] Oniszk-Popławska A, Biogazownie jako źródło ciepła i energii elektrycznej, in Targi INSTALACJE 2010. Branża Instalacyjno-Grzewcza w Polsce – 2009 rok i co dalej. Poznan; 2010.
[42] Józwiak M. Czy opłaca sie budowac biogazownie w Polsce? In: Finansowanie budowy biogazowni szansa na zrównowazony rozwój energetyki odnawialnej. NFOSiGW; 2008.
[43] Council of Ministers, ROZPORZ$\mathcal{A}$ DZENIE RADY MINISTRÓW z dnia 24 grudnia 2007 r. w sprawie Polskiej Klasyfikacji Działalności (REGULATION OF THE COUNCIL OF MINISTERS on the Polish Classification of Activities (PKD) adopted on 24th December 2007: Warsaw.
[44] PPE. Polish power exchange; 2010 [Last access: 30.05.10] http://www.tge.pl/.
[45] IPiEO, ARR. National Report on current status of biogas production – Poland. WP5 – deliverables 5.1, IEE, Editor. Warsaw: Instytut Paliw i Energii Odnawialnej, Agencja Rozwoju Regionalnego; 2010. p. 13.